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Increasing the Resilience of Cultural Heritage to Climate Change through the Application of a Learning Strategy

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Abstract. There is growing concern about the threat posed by climate change to cultural heritage, notably to World Heritage properties. Climate change is triggering changes in rainfall patterns, humidity and temperature, as well as increasing exposure to severe weather events that can negatively impact on cultural heritage materials and structures by enhancing the mechanical, chemical and biological processes causing degradation. In response to this climate change challenge, the Climate for Culture (CfC) project, funded by the European Commission, investigated the impacts of climate change on the European cultural heritage through the use of a high-resolution regional climate model that projected future changes in climatic conditions, and simulated the future conditions of the interiors of historical buildings and their impacts on the collections they hold using building simulation tools. This paper compares the climate change impacts on cultural heritage identified by the CfC project with semi-structured interviews with experts working on cultural heritage preservation in Norway, Italy and the UK. Hence, the perceptions of the cultural heritage community on the impacts of climate change on heritage assets are first explored, which are then compared with the risk matrices produced by the CfC project as a decision-support tool to inform managers involved in the preservation of cultural heritage. In addition, the learning strategy underpinning examples of climate change adaptive measures applied to cultural heritage is discussed. Through the identification of the current learning strategy in the case study sites, this research highlights the lack of dissemination of the outcomes of scientific research to managers of cultural heritage in the context of adaptation to climate change impacts.

Keywords: Resilience, Adaptation, Climate Change, Cultural Heritage, Learning Strategies.

1 Introduction

Cultural heritage is susceptible to fluctuations in climatic conditions and extreme weather events. Changes in temperature, precipitation and relative humidity can impact on the historical materials and structures that comprise cultural heritage assets, through variation in the mechanical, chemical and biological mechanisms of material and structural degradation. Cultural heritage is also affected by extreme sea level rise and flooding, for example during storm surges, causing coastal impacts and landslides; the intensity and occurrence of which are predicted to increase with climate change. Coastal erosion is also seen as a particular risk for heritage, potentially resulting in the complete loss of sites (Sabbioni et al., 2010, Brimblecombe et al., 2011).

To assess the risk that changes in climatic conditions pose for cultural heritage, two projects were funded by the European Union: the Noah's Ark project (2004-2007) and the Climate for Culture (CfC) project (2009-2014). Both projects developed predictive models of the impacts of climate change on cultural heritage in Europe. This was done mainly through the development of maps projecting variations of climatic conditions into the future, which were related in turn to the mechanical, chemical and biological degradation mechanisms that affect cultural heritage (Sabbioni et al., 2010, Leissner et al., 2015, Bertolin and Camuffo, 2014, Sabbioni et al., 2008). These two projects attempted to overcome a barrier to climate change adaptation in the field of cultural heritage by introducing climate modelling and building simulation tools, an approach not commonly used within the heritage sector.

Scenarios developed by projects of this sort can be used to inform stakeholders about the possible risks and impacts that are predicted to affect cultural heritage in the near and far future. There is an associated urgency to protect threatened heritage sites from climate change impacts, for which these new tools may be expected to find valuable application. However, to date it has not been possible to evaluate the impact of such projects' outputs and predictions on conservation awareness and practice. Have these scenarios been used in cultural heritage preservation or have they remained a mere scientific exercise?

This paper aims to compare the results from the scientific community, focusing specifically on the more recent CfC project, with the perceptions and awareness of the cultural heritage preservation stakeholders' community in selected locations in Europe. The paper also examines whether there are connections between awareness of climate change risks and the propensity to take adaptive actions as well as identifying the learning process behind the adopted adaptation strategies.

2 Cultural heritage and climate change

Most research published to date in the field of climate change and cultural heritage has focused on assessing the risks and impacts of climate change on cultural heritage in Europe (Sabbioni et al., 2010, Bertolin and Camuffo, 2014, Leissner et al., 2015, Cassar, 2005, Brimblecombe et al., 2011, Cassar and Pender, 2005). The CfC project developed a methodology to assess the climatic risks for the indoor European cultural heritage. Maps, at a 12.5 km resolution, projecting potential scenarios of change for a number of climatic variables affecting cultural heritage, were developed using the Regional Climate Model (RCM) REMO for the baseline (1961-1990), near future (2021-2050) and the far future (2071-2100) time-periods. The project used two moderate greenhouse gas (GHG) emission and concentration scenarios: the A1B and the Representative Concentration Pathway (RCP) 4.5 of the Fourth and Fifth Assessment Report of Intergovernmental Panel on Climate Change (IPCC), respectively (IPCC, 2000; IPCC, 2014; Thomson et al., 2011). Potential variations of the mechanical, chemical and biological indoor degradation of light-weight (i.e. wooden) and heavy-weight (i.e. masonry) buildings into the future were estimated on the basis of those climate change projections (Leissner et al., 2015).

Although there is increasing research on climate change impacts on cultural heritage, there remains a paucity of studies reporting on the awareness of the cultural heritage community on those impacts and the use of the outcomes from such research in adaptation decision-making. The way decision-makers perceive the risks and impacts of climate change is likely to influence the choice and development of adaptation strategies (Gray et al., 2014), but this has yet to be examined in the field of cultural heritage.

Research accomplished to date on adapting our cultural heritage to climate change centres on the dissemination of guidelines and recommendations to implement adaptation measures (Sabbioni et al., 2010, Sabbioni et al., 2008, Heathcote et al., 2017, Haugen and Mattsson, 2011, Cassar, 2016, Pollard-Belsheim et al., 2014, Carmichael et al., 2017a, Fatorić and Seekamp, 2017a, Grøntoft, 2011, Hall et al., 2015, Hall, 2015) and on the identification of opportunities and barriers to adaptation (Phillips, 2014, Fatorić and Seekamp, 2017b, Carmichael et al., 2017b, Casey, 2018, Sesana et al., 2018). Preserving cultural heritage from the impacts of climate change requires a shift from reactive to proactive adaptation (Sesana et al., 2018). However, the process of deciding when and how proactive adaptation is appropriate, and its connection to the knowledge base amongst stakeholders is unclear. How do decision makers react to climate change impacts? Where do they get the knowledge required to inform the adaptation process? What approach do they follow to gather and apply that knowledge? Building on the knowledge requirement for adaptation reported in the literature (Sesana et al., 2018), we argue that an increased understanding of the learning process underpinning the adaptation measures that have occurred in cultural heritage preservation would better inform the management of cultural heritage (McDonald-Madden et al., 2010, Williams, 2011).

3 Methodology

In this paper, a comparison between qualitative data obtained from semi-structured interviews with the cultural heritage management community and a quantitative risk assessment developed as part of the CfC project using regional climate change projections is made. Information from semi-structured interviews conducted as part of a larger study (also presented elsewhere, e.g. Sesana et al. 2018) were extrapolated in order to understand the perceptions of climate change impacts on cultural heritage amongst selected experts working in the field of cultural heritage in three European countries: Norway, Italy and the UK. The data collected during those interviews were then compared with the results from the CfC project, which estimated the impacts of future climate change on cultural heritage in sites or in the region where the interviewed stakeholders are located. In addition, the data from the interviews were used to identify examples of climate change adaptation measures adopted and matching the adaptation approach to two learning strategies.

3.1 Qualitative data

Forty-five semi-structured interviews were conducted (Table 1). The interviews focused on three main questions, namely (1) Are you aware of any changes in the climate that are affecting cultural heritage? (2) Are you aware of climate change projections for your country? (3) Are you aware of any examples of adaptation measures or case studies where adaptation measures have been adopted to preserve cultural heritage from climate change impacts?

Table 1. Professional affiliations of the interviewees**.**

Interviewees		Number of interviews
Academics and researchers		19
Managers of cultural heritage		26
	Total	45

The cultural heritage experts interviewed and falling within the 'academics and researchers' category are specialists in anthropology, archaeology, architecture, biology, conservation science, climate science and geology, while the other category comprises heritage site managers and coordinators, sustainability officers and urban planners, and architects and conservators working within heritage sites. The interviews were audio recorded, transcribed and analysed using the NVivo software. Ethical approval was sought and obtained through the University of the West of Scotland procedure.

3.2 Quantitative data

The CfC project assessed the risks of climate change on cultural heritage for locations distributed over a regular grid across Europe. Hence, on the basis of the outcomes of the CfC project, matrices compiling the risks of climate change were developed by obtaining data for the grid points in the three countries were the interviews took place, i.e. Norway, Italy and the UK, as depicted in figures 1 to 3, with the coordinates of the grid points shown in Table 2 to 4. The information from the CfC project has been re-analysed and reinterpreted for the purpose of producing the matrices for the current paper. These locations were selected by the CfC project team so as to represent a range of different geographical contexts in each country considered. Projections for a number of climatic variables for the grid cells centred on the points with the coordinates shown in Table 2 to 4 were obtained from the RCM, which were then used to determine the risks of those climatic factors on cultural heritage. For this purpose, the climate change projections were coupled with buildings simulation tools to estimate mechanical, chemical and biological degradation damage variables. The matrices provided in this paper (Figures 4 to 7) show the cumulative mechanical, chemical and biological risks for the indoor cultural heritage depending on structure typology, location of the site and the time-scale of the projections. Loli and Bertolin (2018) provide more details on the development of the matrices.

Fig. 1. Locations where climate change risks on cultural heritage were estimated in Norway as part of the CfC project. Map data ©2018 Google.

Table 2. Locations of variables (Latitude, Longitude and ID) simulated in the CfC project for Norway.

Country	ID	Lat.	Long.
Norway	1	69.2898	17.5711
	2	69.2659	21.1079
	3	69.1791	24.6277
	4	66.6144	14.4121
	5	63.8928	11.7972
	6	62.2671	6.5031
	7	62.4467	9.2598
	8	60.9630	6.9321
	9	61.1359	9.5886
	10	61.2618	12.269
	11	59.6575	7.3273
	12	59.8244	9.8912
	13	58.3510	7.6928

Fig. 2. Locations where climate change risks on cultural heritage were estimated in Italy as part of the CfC project. Map data ©2018 Google.

Table 3. Locations of variables (Latitude, Longitude and ID) simulated in the CfC project for Italy.

Country	ID	Lat.	Long.
	1	46.5594	10.0936
	2	46.6832	12.0026
	3	45.0934	8.4419
	4	45.2468	10.2938
	5	45.3674	12.155
Italy	6	43.9338	10.4849
	7	44.0515	12.3004
	8	42.7353	12.4395
	9	41.5003	14.3083
	10	39.8539	9.32880
	11	40.2311	16.0938
	12	37.5451	14.5604

Fig. 3. Locations where climate change risks on cultural heritage were estimated in the UK as part of the CfC project. Map data ©2018 Google.

Table 4. Locations of variables (Latitude, Longitude and ID) simulated in the CfC project for the UK.

Country	ID	Lat.	Long.
United Kingdom	1	58.1739	-4.9767
	2	56.9151	-4.2360
	3	55.6523	-3.5437
	4	54.3858	-2.8948
	5	53.1160	-2.2848
	6	53.4525	-0.1554
	7	51.8433	-1.7098
	8	52.1706	0.3652

4 Results and discussion

4.1 Perception and awareness of climate change impacts on cultural heritage

The interviewees' answers to the question on whether they are aware of climate change impacts on cultural heritage assets are summarised in Table 5. The responses are divided according to the three countries in which the interviews took place and according to the background of the interviewees (i.e. whether they are academics or cultural heritage professionals, for example professionals involved in the management of cultural heritage). All interviewees in Norway and Italy noted impacts of changes in climate on cultural heritage, but this figure was found to be lower in Italy, particularly for the managers of heritage sites.

Table 5. Interviewees' answer to the question: "Are you aware of any changes in the climate that are affecting cultural heritage?"

		Academia	Managers of cultural heritage
Norway	Yes	100%	100%
	No	0%	0%
	Some	0%	0%
Italy	Yes	66.6%	14.3%
	No	16.7%	71.4%
	Some	16.7%	14.3%
UK	Yes	100%	100%
	No	0%	0%
	Some	0%	0%

Table 6 provides examples of direct quotations from a selected number of interviews to the first question mentioned in Table 5. These quotes provide examples of specific impacts perceived to be occurring by the interviewees.

Table 6. Examples of interviewees' answer to: "Are you aware of any changes in the climate that are affecting cultural heritage"?

Interviewee	Country	Quotation
Academic	Norway	"*The weather is wetter; there is much more rain, a lot of river flooding. According to climate change this is more dangerous, more rain, strong rain which makes the river flood. You have also the rise of sea level. There are some areas of cultural heritage that are exposed to that for example the houses exposed to the coast. (...) The rise of humidity is a danger to older building construction."*
WHS coordinator	Norway	"*We have a general knowledge about prediction of climate change. (...) rainfall (...) flood (...) erosion (...) heavy rain and landslides*."
Academic	Italy	"*The change of precipitation pattern, the seasonality of the precipitation, drier summers, wetter winters, an increase in the frequency of heavy rain events. It is not the quantity of precipitation that is changing, what is projected to change is the number of extreme events and their seasonality. The changes in the hygro-thermal parameters such as temperature and relative humidity will influence the cohesion and cracking (of historical materials) due to salt crystallization. Or (they will influence) the biological growth*."
Member of governmental institution	Italy	*"I am aware of climate change, but I am not aware that climate change is influencing cultural heritage."*
Academic	UK	"*Rainfall has increased, and temperature has increased by half a degree, at least on average. (...) Increase in intensity of rainfall. The guttering is not good enough and we probably look at an increase in soil moisture, so probably the largest problem is rising damp in buildings."*
Member of governmental institution	UK	"*Increased precipitation, rising temperature, higher humidity and that's important because insects like humidity. We are getting less frost so the freeze and thaw is getting better. Frost does not matter if the building is dry, but if the building is wet it is a problem. (...) we have quite a lot of data here, which essentially show wetter winter, drier summers and intense rainfall in summer. So it is not saying that it going to be drier, but that summer is drier*."

The interviewees' answers in Table 7 highlight where the interviewees have consulted or have seen climate change projections for their country. The answers are divided, as in Table 6, according to the three different countries investigated and the field that the interviewees work in. In all three countries, the percentage of interviewees aware of climate change projections for their country is higher for the academics than the managers of the heritage sites, but the difference between the two groups of stakeholders is much smaller in the UK. Managers of heritage sites in Italy appear to be unaware of climate change projections for their country. This is in line with the results depicted in Table 5 as one could argue that as the changes in climate that have occurred to date are not perceived to have impacted cultural heritage assets, the stakeholders are less likely to consult projections of future climatic changes

Table 7. Interviewees' answer to the question: "Are you aware of climate change projections for your country?"

		Academia	Cultural heritage management and preservation
Norway	Yes	75%	40%
	No	0%	0%
	Some	25%	60%
	No Answer	0%	0%
Italy	Yes	80%	0%
	No	0%	14.3%
	Some	0%	0%
	No Answer	20%	85.7%
UK	Yes	70%	61.5%
	No	0%	7.7%
	Some	20%	23.1%
	No Answer	10%	7.7%

Table 8 summarises the main consequences of climate change on cultural heritage as identified by the interviewees in the three selected countries.

Table 8. Consequences of climate change on cultural heritage as identified by the interviewees.

Norway	Italy	UK
Increase in biological growth	Decline in freeze-thaw weathering	Stone erosion is a risk
Increase in insect growth	Decrease of decohesion of porous materials due to a decrease of freeze-thaw cycles	Increase in biological growth
Increase of biological patina due to increased humidity and increased concentration of nitrogen in the air	Change in decohesion and in cracking of materials due to a change in salt-crystallization phenomenon under a variation of temperature and relative humidity	Increase in insect growth
Increased humidity	Gutters may not cope with extreme rainfall	Increase of biological patina due to increased humidity and increased concentration of nitrogen in air
Warmer winters increases decay of wooden structures	Accelerated decay of roofs under increased rainfall	Water ingress into buildings
Warmer and more humid climate is not good for timber structures	Sudden changes in temperature crossing the zero degrees with subsequent serious condensation	Dampness penetration into buildings
Fungal decay	Increased condensation in summer	Water saturation
Blackening of wooden panelling	Condensation over 70-75% of humidity can lead to biological growth. In Italy there is an alternation of wet and dry periods with sun.	Blockage of gutters
	Anomalous condensation on frescoes	General increased in decay and particularly for sandstone buildings
		Climate change is a risk multiplier
		Increased decay on unroofed castles and monuments
		Decrease of freeze-thaw cycles

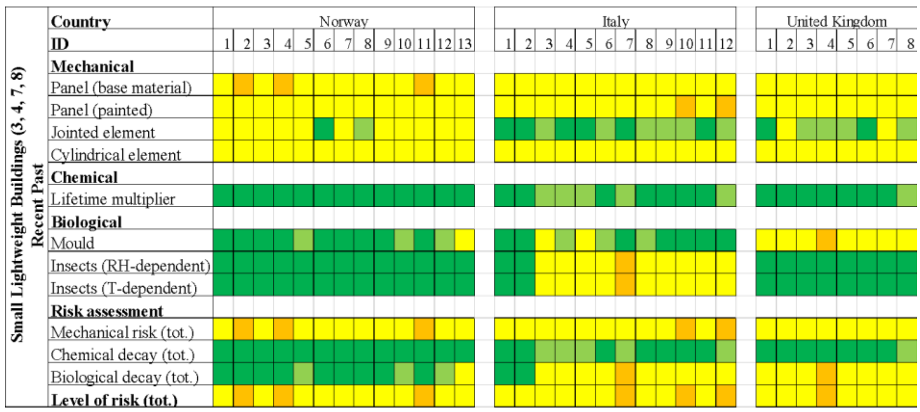
A comparison between the risk matrices shown in the subsequent section with the interviewees' answers reveals that, overall, the interviewees are aware of climate change impacts on cultural heritage. However, in Italy, there is a contrast between the recognition of climate change impacts affecting cultural heritage amongst heritage managers in comparison to the perceptions of academics, with the latter appearing more knowledgeable on this issue. In all three countries, heritage site managers showed less awareness of climate change projections than the academics. All interviewees were aware of climate change, but some of them were not aware of the possible consequences for cultural heritage. In fact, some interviewees appeared more knowledgeable about climate change mitigation (i.e., reducing the carbon footprint of historical buildings) rather than on the risks and impacts of climate change on the heritage sites; the latter was particularly the case at the management level in Italy. One reason might be that northern European countries may already be experiencing more negative impacts from climate change on cultural heritage in comparison to the Mediterranean region. This could be investigated further by consulting a larger sample of stakeholders over a larger geographical area.

It was also found that the European projects mentioned above, i.e. Noah's Ark and CfC, were known mostly in academia and not amongst managers of cultural heritage. Moreover, the majority of interviewees that indicated considering climate change impacts in their decision-making did so using readily available and nationally produced climate change projections (for example, those produced by the United Kingdom Climate Impacts Programme (UKCIP) in the UK and the report Climate in Norway 2100 (Hanssen-Bauer et al., 2017)) rather than using the maps developed in projects such as CfC that estimated potential changes in the degradation of historical materials of cultural heritage resources on the basis of regional climate change projections. With regards to the impact of such project outputs, and to emphasise the need for improved communication, an interviewee mentioned the following:

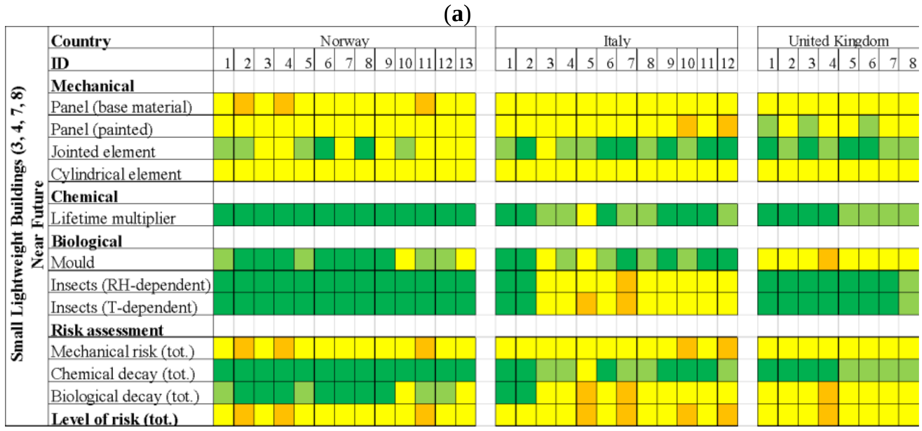
> "*The problem is that these instruments should be known by the people that need to use them. Instead, a lot of times, those operating in the heritage sector do not know what has been developed and produced (at a research level). Who's guilty? The one who developed the product or the one who needs to use it? There is a link that is missing. We need to understand if those in charge of cultural heritage have this sensibility. Climate change is not considered and this is the major problem. There is a need for a connection between local realities and research centres, and this connection should be made by governmental institutions*."

4.2 Projections of climate change risks on cultural heritage

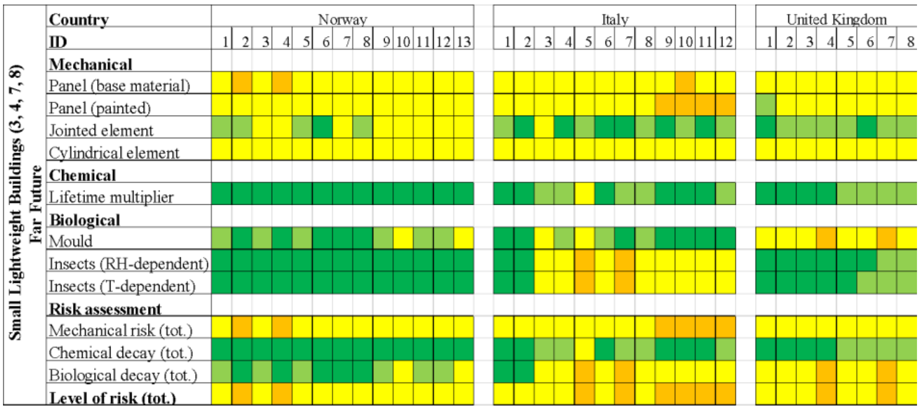
Figures 4-7 summarise the mechanical, chemical and biological risks projected by the CfC project in different locations in the three studied countries. The risks of climate change were estimated for two different building typologies: lightweight (i.e. wooden) and heavyweight (i.e. masonry) buildings for the baseline ((a) 1961-1990), the near future ((b) 2021-2050) and the far future ((c) 2071-2100). The ID numbers refer to the locations where climate change risks on cultural heritage are estimated in Norway (Figure 1), Italy (Figure 2) and the UK (Figure 3). Six levels of decay were depicted using different colours to display a combination of the likelihood and the impact of the decay: very low (green), low (light-green), medium (yellow), medium-high (orange), high (red) and very high (dark red). The boundary value for each decay level was established according to the variables identified in the CfC project as described in Loli and Bertolin (2018, p. 6).



(a)

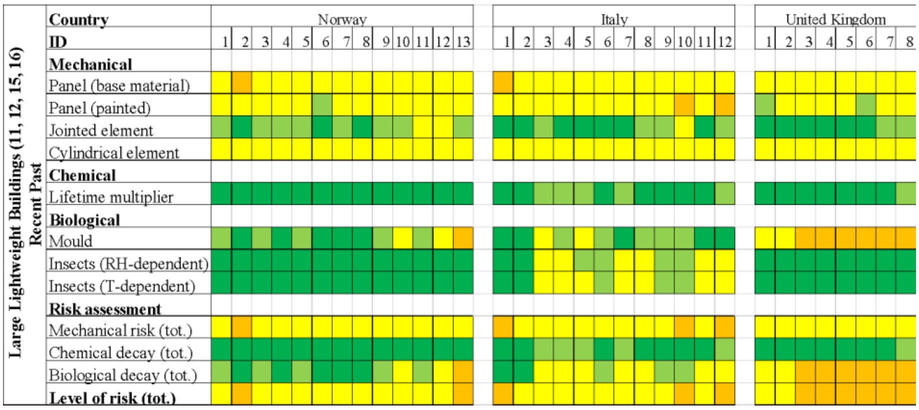


(b)

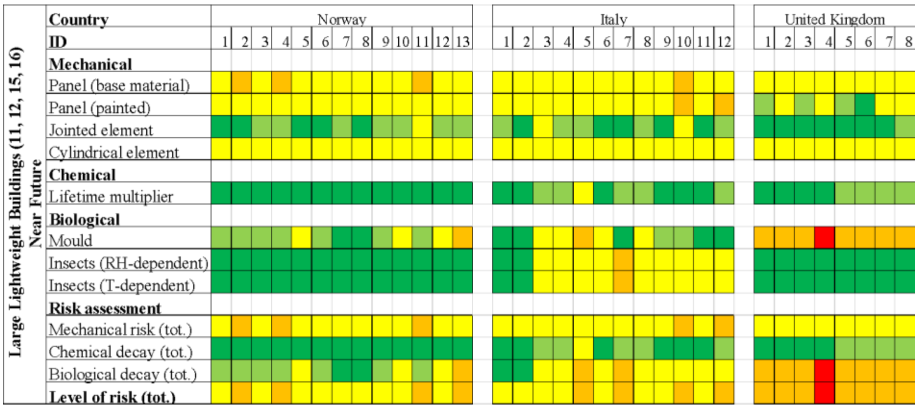


(**c**)

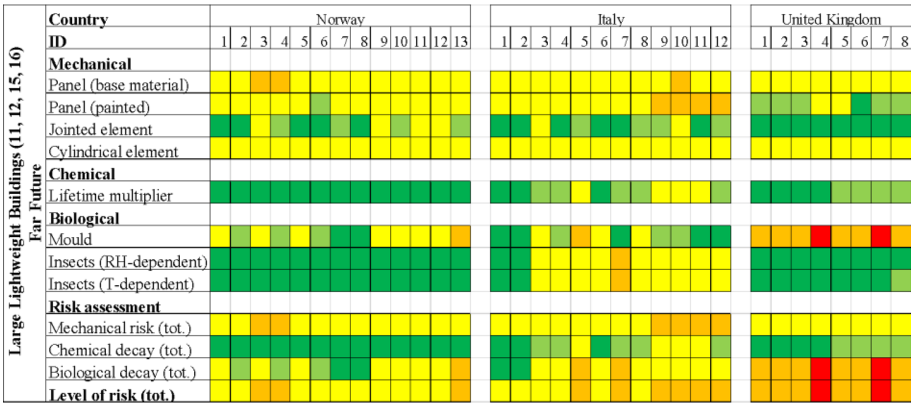
Fig. 4. Risk assessment matrix of the deterioration of small lightweight buildings for the: (**a**) Baseline(1961-1990); (**b**) Near Future (2021-2050); (**c**) Far Future (2071-2100).



(**a**)

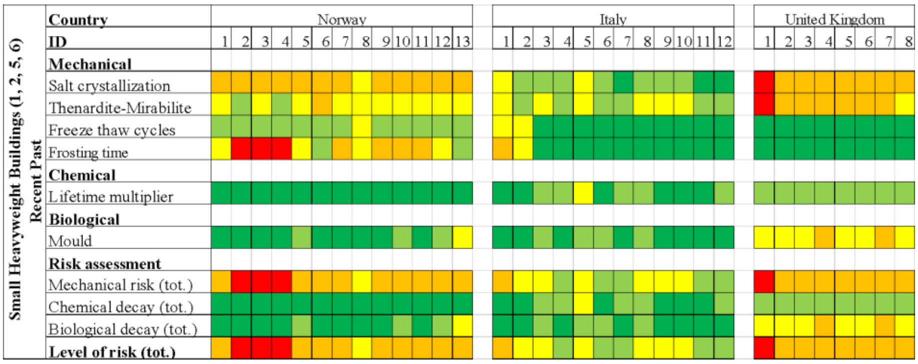


(**b**)

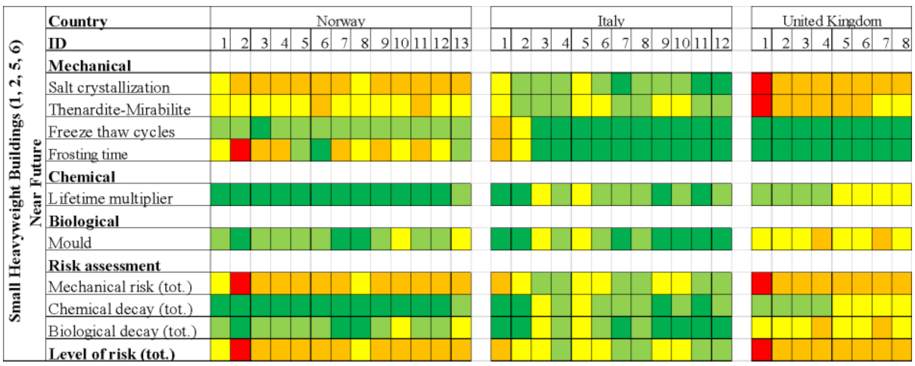


(**c**)

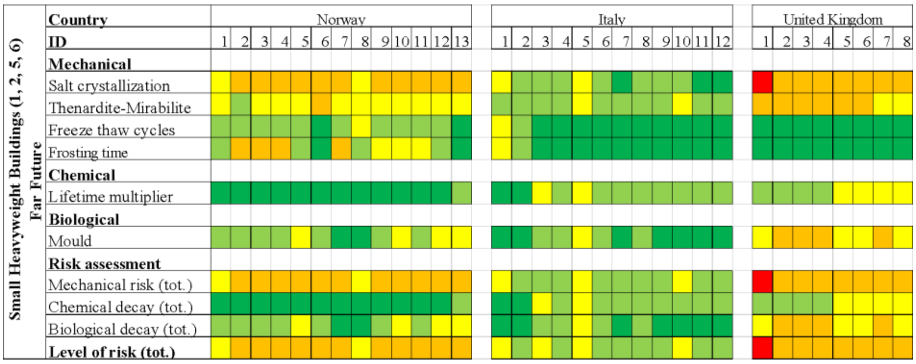
Fig. 5. Risk assessment matrix of the deterioration of large lightweight buildings for the: (**a**) Baseline (1961-1990); (**b**) Near Future (2021-2050); (**c**) Far Future (2071-2100).



(**a**)

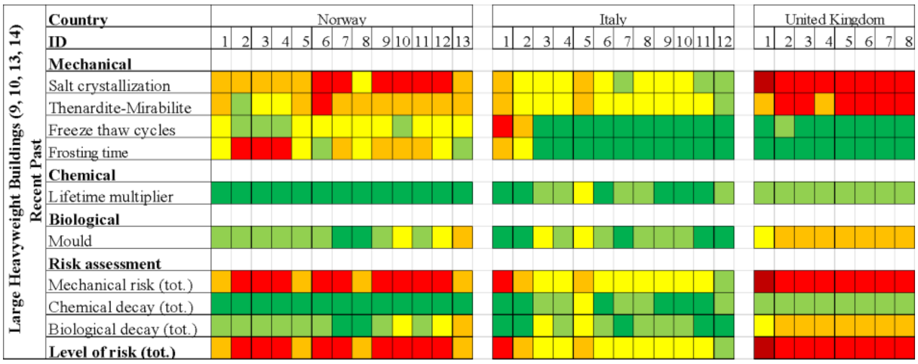


(**b**)

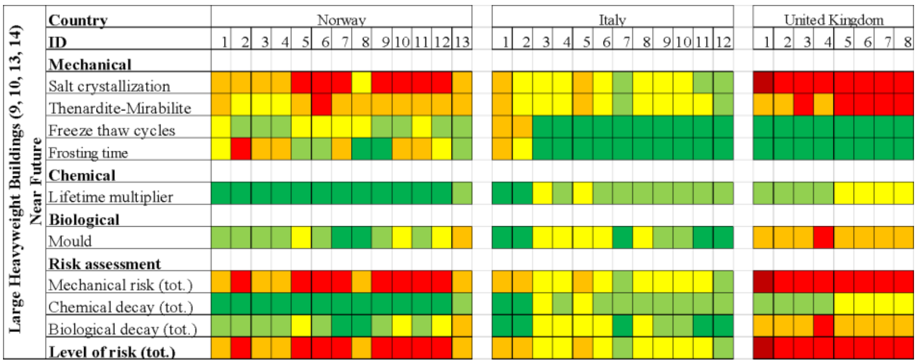


(**c**)

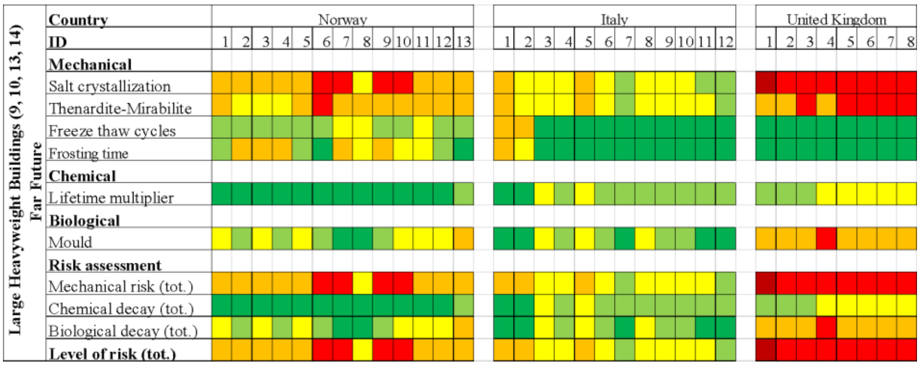
Fig. 6. Risk assessment matrix of the deterioration of small heavyweight buildings for the: (**a**) Baseline (1961-1990); (**b**) Near Future (2021-2050); (**c**) Far Future (2071-2100).



(**a**)



(**b**)



(**c**)

Fig. 7. Risk assessment matrix of the deterioration of large heavyweight buildings for the: (**a**) Baseline (1961-1990); (**b**) Near Future (2021-2050); (**c**) Far Future (2071-2100).

If we compare the risks projected by the CfC project with the issues of concern identified by the interviewees we can see that:

- The issues of concern identified by the stakeholders agree with the projected climate change risks depicted in the matrices, however, the matrices are more detailed in terms of information on the specific decay mechanisms and types, and linking this to specific locations. Accordingly, the matrices confirm the increase in biological degradation on Norwegian cultural heritage perceived by the interviewees. The matrices also show a decrease in mechanical risk due to a decrease in the number of freeze-thaw cycles and a change in the mechanical risk for salt crystallization for some parts of Norway. In Italy, the matrices classify an increase in decay for the wooden cultural heritage, showing a medium-high risk in some locations. Few changes were identified for masonry buildings as a result of a decrease in decay due to a reduction in the freeze-thaw cycles in the northern regions of Italy. In the UK, the interviewees recognized the increase in biological decay as indicated in the matrices with a high risk for wooden buildings and a high or medium-high risk for masonry buildings mainly by mould degradation. An increase in the chemical risk on cultural heritage was also identified for the UK. Moreover, the interviewees pinpointed an increase in mechanical degradation, that is confirmed by the matrices which show that UK cultural heritage is currently at risk of mechanical degradation, and that this risk will remain high in future.

- Some of the interviewees identified climate change risks for the more common building materials in their country, i.e. wooden buildings in Norway and stone buildings in the UK. For instance, Norwegian interviewees expressed awareness of the possible increase in decay of wooden built heritage, but they did not show awareness of the future increase of decay on masonry buildings, mainly by salt weathering, which is highlighted by the CfC projections (high mechanical risk for stone).

- If we compare the matrices with the stakeholders' answers, we can see that where the stakeholders' perceptions generally agree with the risks identified in the matrices and hence stakeholders' awareness of climate change impacts is high such as observed for the UK site, the risks of climate change on cultural heritage are also projected to be higher. The opposite is also true, i.e., where awareness of climate change impacts is low as seen in the management of the heritage site in Italy, the projected climate change risks are also lower. On the basis of this result, one could argue that interest in climate change impacts by the stakeholder's community is a reactive consequence to the current threats of climate change on cultural heritage and in locations where climate change is not yet perceived as a threat to cultural heritage, there is less interest in climate change and thereby lower awareness.

- Some of the climate change impacts identified by the interviewees, for example, the increase in condensation mentioned in Italy, are not specifically considered in the matrices. This suggests that consultation with local stakeholders could also potentially inform the risk assessment. A two-way knowledge exchange rather than a one-way knowledge transfer between the scientific and users' communities would clearly be beneficial as the results of this study demonstrate.

If the stakeholders' perceptions of climate change risks on cultural heritage would show greater awareness of what the problems are, for instance, as a result of consulting risk matrices such as those produced by the CfC project, would this have an influence on the adaptation process? To answer this question the learning process behind the adaptation measures and strategies identified by the interviewees was analysed, and is presented in the next section.

4.3 The learning process behind the adaptation of cultural heritage to climate change

In this section, models of single and double loop learning (Argyris and Schön 1987) are first presented. Then, the adaptation process as deduced from the interview transcripts are fitted to each learning loop.

4.3.1 Single loop learning process

A single loop learning process consists of an automatic reaction to a problem with little or no learning occurring during the process (Figure 8). The final outcome is achieved without taking steps to improve the understanding of the causes of the problem and hence potentially the long-term resilience of the site to the selected adaptive action against future climatic changes, for instance (Argyris and Schön, 1987).

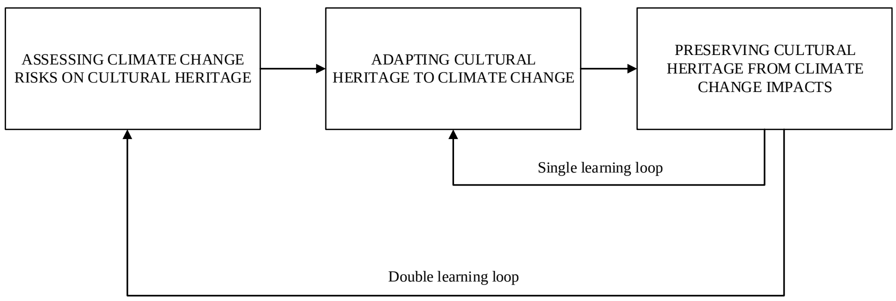


Fig. 8. Single and double learning loop applied to the preservation of cultural heritage from climate change impacts.

The existence of a single loop learning in the experts' responses to climate change impacts on heritage and the identification of adaptation solutions can be seen in the following quotes from selected interviewees:

> *"Here in Norway, to adapt cultural heritage located near the coast from sea level rising they moved the small groups of wooden houses to the internal land."* (Interviewee, Academic)

> *"In Cesenatico the house of Marino Moretti on Porto Canale can be flooded and on the ground floor you cannot put any of the museum collections."* (Interviewee, researcher)

> *"I am aware that in some cases they increased the capacity of gutters and downpipes, because they can be overwhelmed by the volume of water and then*

> *it overflows and (the water) can come into the building."* (Interviewee, Member of governmental institution)

These are three examples of reactive adaptation measures adopted after hazardous events affected cultural heritage sites. The action adopted is a reaction to a specific impact, but the response does not involve a deeper consideration or research into the causes for the occurrence of the impact, and a longer-term planned response. In other words, a single loop learning process focuses on the management of the change rather than on the implementation of a long-term strategy.

4.3.2 Double loop learning process

A double loop learning process refers to a rethinking of the current norm, rules and procedures (Figure 8). This type of learning thus requires a certain degree of critical thinking in the identification of the best solution to a problem or to accomplish an objective. Argyris and Schön (1987) considers double loop learning as the best learning approach for addressing problems that can evolve with a change of circumstances.

The double learning loop involves the evolution of the operational schemes and theories behind the action. For example, this is illustrated in the following quote that expresses concerns with regards to planning for the impacts of climate change on a coastal archaeological site in Scotland:

> *"In the World Heritage Site of Skara Brae the effects of climate change are very well known: sea level rise, increased storminess. (...) There are a lot of issues there, trying to understand what is happening with the coastal erosion. (...) There is a hard seawall that did his job (of protection) so far, but there are other questions. At the moment (...) we are studying what happens using laser scanning (…) trying to find out if the sea wall deflects the waves (...) and trying to pull all this information for a better understanding of what is happening so that we can make better plans to mitigate [the risks]. And that has been combined with an annual photographic survey with fixed points for a visual (record) as well as 3D modelling."* (Interviewee, Member of governmental institution).

Within the governmental organization in charge of the preservation of this archaeological site, Skara Brae, a risk assessment for understanding the specific impacts of natural hazards on the site has been developed. For example, the results of this assessment highlight that the site is at risk of groundwater flooding and of slope instability (HES, 2018).

In this example, the adaptation measures to be adopted at the site are informed by projections of climate change risks and by monitoring the site through laser scanning and photographic surveys. This is a longer term adaptation planning process that can be correlated with a double loop learning process. The custodians of the site are not waiting for a disaster to befall the site. It indicates that they have prior knowledge of the likely outcomes of, in particular, extreme events. The learning process behind the collection of this information will be able to inform the adaptation process. The double loop learning process shows that new understanding on the possible climate change risks and vulnerabilities should inform future adaptation interventions. This learning approach may help those involved in cultural heritage preservation in planning preventive adaptation interventions. It might also be used as a re-thinking reactive approach after the occurrence of hazardous events.

5 Discussion and Conclusion

This paper investigated the perceptions and awareness of the cultural heritage community of the risks and impacts of climate change on cultural heritage. The learning process behind the identification and implementation of the adaptation measures adopted by cultural heritage managers to mitigate against specific climate change impacts was also examined, as a way, to assess the potential of scientific information and tools that project climate change risks on cultural heritage to support adaptation decision-making.

A number of interviewees showed awareness of some of the impacts of climate change on cultural heritage. The CfC matrices of risks on cultural heritage, which were developed on the basis of climate change projections from a RCM, or any other tools previously developed can be useful to inform cultural heritage managers or those in charge of cultural heritage preservation on the possible future changes in decay on cultural heritage resources under climate change, but, further efforts are required by the scientific community to disseminate those tools so that site managers can integrate them into cultural heritage management. Simulations such as those produced as part of the CfC project can support and improve effectiveness of adaptation practices. For example, giving heritage site managers quantitative data about the future rate of decay on groups of cultural heritage resources with similar characteristics (e.g. materials, dimensions) according to their locations. However, it should be emphasized that the risks identified and depicted in the figures presented in this paper are based on moderate GHG emission scenarios (and pathways). Given the current population growth projections and our continued reliance on fossil fuels as our main source of energy, the RCP8.5 worst-case emission scenario is becoming a more realistic trajectory, which would result in more drastic climatic changes and consequently a stronger magnitude of the risks and ensuing decay on cultural heritage sites.

Disseminating the outcomes of scientific research on the identification of the risks of climate change on cultural heritage (e.g. Noah's Ark and CfC projects or other developed risks assessments) can increase decision-makers’ awareness on those issues and help in moving forward climate change adaptation. However, this paper identified a lack of communication between the academic and management sector. We believe that there is scope for better designing effective adaptation measures and strategies to preserve cultural heritage against climate change impacts by the application of double loop learning as described in the case of a heritage site in Orkney, Scotland. A double loop learning process can be used to implement preventive measures for the conservation of cultural heritage against the impacts of climate change. The use of this learning mechanism as a preventive measure by cultural heritage site managers (i.e. before a hazardous event occurs) can contribute to increasing the resilience of cultural heritage sites.

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